Title: Enhanced Beam Diagnostics with Existing BPPMs via GPU-powered Multi-Particle Simulation

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Research Goal

This research aims to utilize the multi-particle code, High-Performance Simulator (HPSim), to realistically model the Side-Coupled-Cavity Linac (CCL) lattice of the LANSCE accelerator. This new model would allow us to predict the beam's bunch length (the longitudinal spread), which is unavailable for individual accelerating modules or only accessible at the end of the linac. However, a correct bunch length is critical for the high-energy beam transport after the CCL. Its impact would be most significant in the Proton Storage Ring (PSR), where we should be able to reduce losses for the circulating beam. The PSR is scheduled to have a 25% current increase for the neutron spallation target upgrade at the Lujan Center. A highly bunched beam would be necessary to reduce the particle losses and lower the radiation levels produced from the ring. A realistic HPSim model with >1M macro-particles can help tackle the beam losses at the sub-percent level. This new work would also create a realistic surrogate model for future machine learning projects.

Background & Significance

The LANSCE CCL, comprised of 44 RF modules, accelerates a train of H^- bunches from 100 MeV to its final energy of 800 MeV. The H^- beam is then delivered to several user facilities, as shown in Figure 1. The complexity of the timing patterns for each experimental facility beam and the balance of multiple beamlines increase the difficulty of configuring the accelerating cavities for ideal bunch shape and transport. A swift and successful tune of the CCL maximizes the beam current while minimizing beam losses.

The RF Signature Matching

Since the beginning of LANSCE (formerly as LAMPF) in the 1970s, the tune-up of the CCL was conducted with the iterative "Δt" method [1], a predecessor of RF signature matching (RFSM). With the new instrumentation and readout upgrades [2], for the first time, the tune of the LANSCE CCL RF modules was conducted entirely with the RFSM method this year.

The RFSM is the standard method [3–6] to set an RF cavity to the proper amplitude and phase set points to obtain the ideal energy gain, and is demonstrated in Figure 2. At one downstream Beam Position & Phase Monitor (BPPM), RFSM measures the time-of-flight (TOF) when the beam is

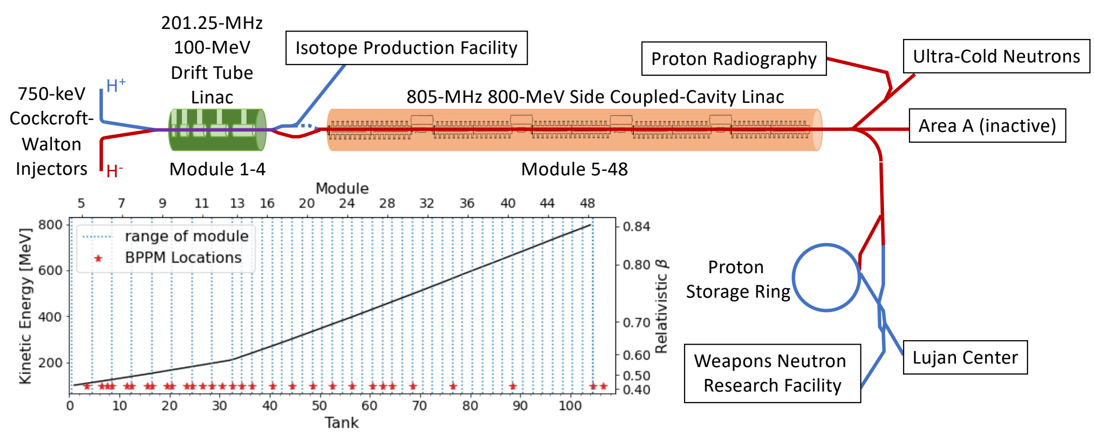

Figure 1: The layout of Los Alamos Neutron Science Center (LANSCE) accelerator and beamlines. The CCL, including modules 5 to 48, is the primary linac that accelerates H^- to 800 MeV. Each module contains 2 or 4 tanks. The lower-left figure shows the beam energy at the exit of each tank and the positions of current BPPMs marked in stars.

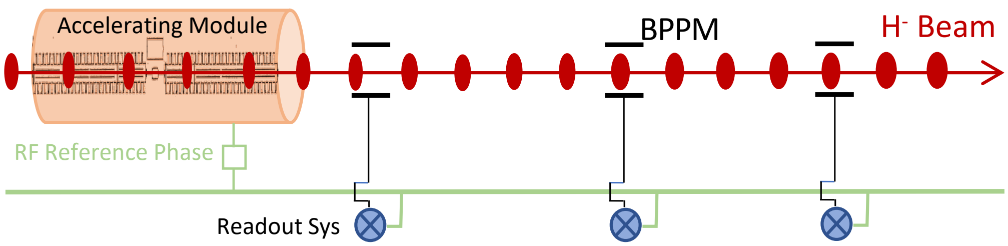

Figure 2: A schematic demonstration of the RF signature matching (RFSM) measurements for the LANSCE CCL. A 150-μs long train of beam bunches ~ 5 ns apart passes the accelerating module and downstream BPPMs for a tune-up. For a given BPPM, the time-of-flight (TOF) is measured between the modules' on (t_{on}) and off (t_{off}) modes. To remove the need for an absolute calibration, the difference, $\Delta t = t_{on} - t_{off}$, is used for modeling. The measured Δt's under a 360° cavity phase scan are compared with a single particle model.

being accelerated, t_{on}, and not accelerated, t_{off}, by the module. The difference, $\Delta t = t_{on} - t_{off}$, is used to eliminate the need for the absolute timing calibration necessary with differing cable lengths. The Δt collected at the first downstream BPPM is often used, but data from more BPPMs can be included. For the RFSM method, a series of TOF differences are measured with a 360° scan of the cavity RF phases. The data is matched with a single-particle model, generating fitted parameters such as the incoming beam energy, phase offsets, and amplitude of the cavity. LANSCE currently uses two downstream BPPMs for RFSM; however, the analysis can include more BPPMs for precision and consistency.

Since it is costly to measure the high-resolution TOF for each of the bunches separated by 4.97 ns within the train of the beam pulse, the raw data undergo a series of online processing [2]. The raw data is grouped into 1-μs blocks, and the analog signals from the four electrodes and the reference signal were conditioned to the 201.25 MHz RF wave. The five signals are then digitized at 4-ns intervals and analyzed with an FPGA to generate positions, intensities, and the relative beam phases to the reference signal. As a result, the beam phase functions as a proxy for TOF. However, to achieve the full potential of the BPPMs, the effects of beam's sub-structures, such as different bunch lengths or out-of-bunch particles, need to be characterized.

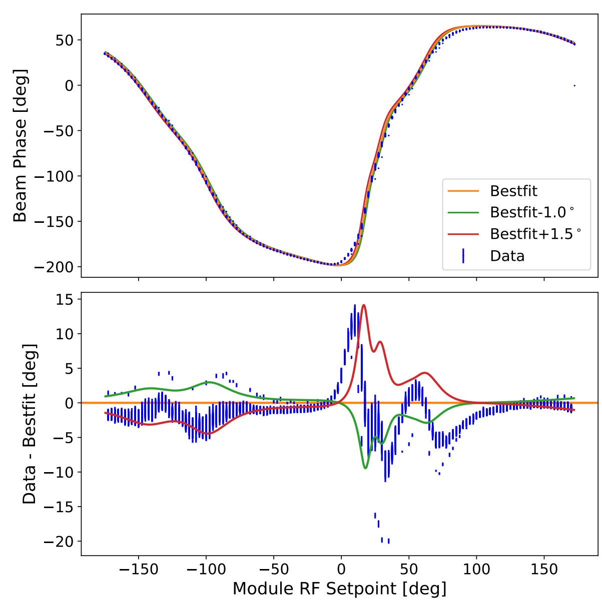

Figure 3: An example of the measured Δt (top) for the RF signature matching and the deviation between data and the single-particle model (bottom). The deviation between data (blue) and the best-fit model (orange) shares similar features with models shifted by $-1°$(green) and $+1.5°$(red) in the incoming beam phases.

Figure 3 shows an example of the RFSM results with the data collected at the first downstream BPPM for module 6. An apparent deviation between the measurements and the best-fit curve exists. The deviation resembles the predictions with slight offsets in the incoming beam phases (red and green curves), indicating possible effects of the bunch length. Furthermore, though the RFSM requires only one BPPM, including data from BPPM(s) further downstream provides extra insights.

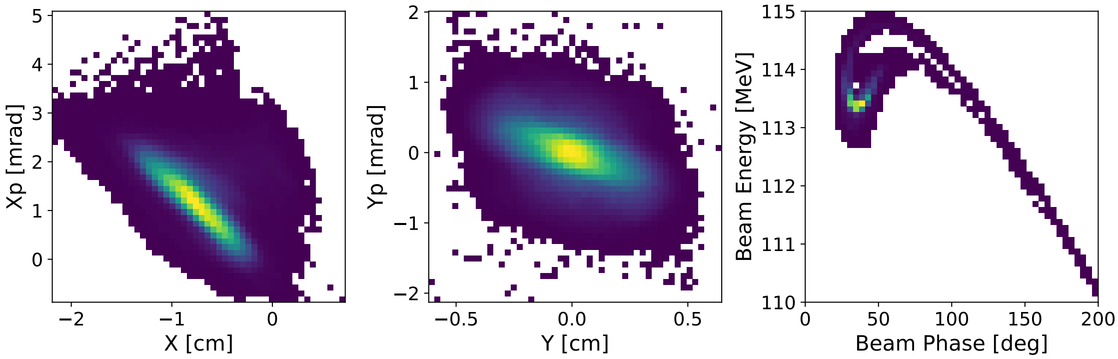

Figure 4: Beam distribution at the first BPPM after module 5 with one million initial macro-particles in HPSim. The long tail of the off-momentum particles is apparent in the plot to the right. A fast and agile multi-particle code is needed to understand beam losses from such tails in real time as the system is being tuned.

HPSim

The HPSim [7, 8] was developed in Los Alamos to provide an agile code for near real-time multi-particle simulations. Such simulations were usually conducted during the initial design stage but are hard to adapt to the ever-drifting operation status. HPSim is based upon the PARMILA algorithms [9], empowered by GPUs to achieve one to two orders of magnitude speed-up. The code is wrapped with a python user interface for flexibility and high-level analysis. Lastly, HPSim directly connects to the LANSCE EPICS [10] control system for real-time monitoring. As a result, HPSim is the optimal tool for building a realistic multi-particle model for the CCL. Figure 4 shows an example of beam distribution of one million macro-particles at the first BPPM after module 5.

HPSim is also the perfect candidate to simulate beam losses, limiting factors for a higher intensity beam. The losses are frequently mitigated with empirical modifications in the CCL, since a physics tune based on an ideal single-particle model cannot address losses at a sub-percent level. Furthermore, with the aging equipment, the amplitudes of some modules are lowered from the design values, shrinking the beam acceptance of these modules. This chaotic, ever-changing system requires a multi-particle model to predict its behavior. We must understand and minimize the losses with the coming installation of the MARK-IV neutron spallation target [11] at the Lujan Center as early as 2022, which requires 25 % more beam current. This analysis method would also prove useful to possible DMMSC project designs should they be staged at the LANSCE facility.

Several efforts have been conducted and approved for maximizing the beam current while limiting the losses. Notably, DR20220074, led by A. Scheinker et al., focuses on the machine-learning approach for adaptive controls next year. A realistic HPSim model of LANSCE's CCL could serve as a surrogate CCL model for this DR, greatly enhancing the effectiveness of the study.

R&D Approach

Preliminary studies

The PI has established an RF signature matching procedure that becomes the major tuning procedure for CCL in 2021. A preliminary study on the effects of the beam bunch size was conducted based on an extension of the single-particle model, as shown in the green and red predicted lines with slight phase offsets in Figure 3. For HPSim, L. Rybarcyk [8] has already developed a phase scan python script with similar data-model discrepancy. Furthermore, the PI has updated all related packages for HPSim on Darwin from its original creation in 2012.

Methods, Technical Challenges & Alternatives

The proposed effort can be separated into three major parts: understanding the data acquisition (DAQ), analysis and modeling, and the final integration of all modules to a linac.

For DAQ, the primary challenge is to understand how the BPPM readout system responds to different bunch lengths and off-momentum particles. The current BPPM system is very limited in its data resolution and sensitives to the beam intensities. To resolve this challenge, we will directly analyze the raw signal from the four plates of the BPPMs at high timing resolution and, if needed, build a model to understand the electromagnetic responses. If an alternative algorithm is needed to capture more information, it is possible to update the FPGA code.

Another technical challenge with the current DAQ is the asynchronous values for the BPPM measurements. The current EPICS system returns BPPM measurements extracted from different beam pulses, introducing a pulse-to-pulse uncertainty. It is currently not possible to see if an aberration is present for a single pulse. For this same reason, a synchronous readout algorithm was implemented at SNS at Oakridge. The LANSCE controls software team is working on a similar solution. If the bandwidth is insufficient to transfer the complete waveform of the necessary BPPMs, a section of the beam pulse can be chosen to maximize efficiency. Another alternative would be to wait until all data were recorded before sending another beam pulse.

For model development, the challenge will be to construct a beam with *N* particles of 6*N* degrees of freedom (*N*>1M) from a few representative parameters, and the prediction needs to be consistent with the BPPM measurements. The incoming beam will be built in HPSim from the source, verified with different diagnostics scattered before and within the CCL. For example, in the Drift Tube Linac (DTL), the initial energy spread of the beam can be measured via an absorber-collector pair, which only measures beam current above an energy threshold. The bunch length can be measured with the new Beam Shape Monitor system [12] between modules 3 and 4 in the DTL. Data from the emittance stations and wire scanners will be used to constrain the transverse distributions. It will be challenging that not all variables can be observed, and their inter-relationships can not be clearly identified. We will include some non-observable parameters, such as variable correlations, as nuisance parameters with estimated constraints in the fitting process. Furthermore, we will test different hypotheses on how different beam properties are assigned to each simulated macro-particle.

We will also study the difference between the CCL model and the performance of the actual machine. The HPSim adopts the "drift-kick-drift" algorithm for the particle transformation at the RF gap with a transit-time factor [13]. This method has been tested in PARMILA and benchmarked with other codes [8]. However, the final machine performance might differ, or dimensional errors could exist. To attack these challegnes, we can utilize the inter-tank BPPMs in earlier modules to narrow our range to a single tank instead of the whole module. Moreover, we can parameterize the dimensional errors in the HPSim and marginalize over these nuisance parameters. At least, we can quantify the effects with the known tolerance.

Last, with the individual module understood, the integration of the whole simulated linac will be compared with the measured phases at all BPPMs along the CCL simultaneously. The energy spread will be benchmarked at a downstream wire-scanner where the beam is maximally bent so that the momentum spread is manifested in the horizontal distribution. There are a few technical challenges to match the BPPMs measurements and the HPSim model. First, the beam current increases significantly compared to the lower peak in tuning. Moreover, a slight deviation at the beginning of the CCL will be greatly amplified at the end. We plan to overcome these problems via inserting virtual elements to adjust the phase advances in HPSim. Furthermore, the RFSM procedure has been tested at a higher peak current with some precautions. The data collected can be used to understand the differences in the peak current.

Expected results

The first expected result is the development of a realistic HPSim model that is consistent with BPPM measurements under RFSM method with an uncertainty up to 1°. The realistic model should also provide extra beam properties, such as the bunch length. The complete integration of the CCL HPSim model will be consistent with all the BPPM measurements in operation, providing insights for loss minimization. The complete model will also serve as a representative surrogate model for LANSCE machine learning projects.

Schedule and Milestones

Before the end of the two-year ECR project, we will have two beam run cycles to take measurements. Preceding each run cycle, we will focus on model development based on existing data. Within each run cycle, we will utilize beam development time to test and verify our model. Figure 5 shows the Gantt chart for the proposed schedule. For DAQ development, milestone (1) will allow synchronous readouts for all BPPMs and verify whether the current BPPM readout algorithm needs an update. If so, an update will be tested at the beginning of the second run cycle for milestone (2). For the modeling and benchmark, by the end of the first run cycle, building a realistic HPSim model for individual modules will be milestone (3). Milestone (4) is to verify the integration by the end of the second run cycle.

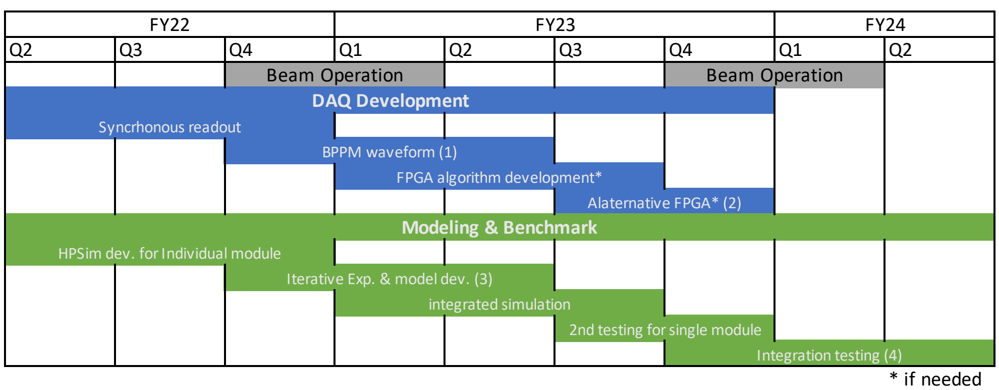

Figure 5: Scheduling for the ECR project.

Mission Relevance & Program Development Plan

Accelerators worldwide would benefit from the additional beam parameters obtained from the RFSM procedure for enhanced understanding of the beam properties. This research project is crucial for the upcoming 25% current increase at the Lujan Center after the new MARK-IV target installation next year. Higher neutron intensity would benefit nuclear, neutrino and some material science experiments at the Lujan Center [11]. Last, a realistic HPSim model will help the modernization of LANSCE and future LANL projects such as DMMSC, as it becomes a surrogate model for training of future machine-learning-based control systems.

Budget Request Justification

As all the equipments already exist for the DAQ and the computer resource is provided by LANL's Institutional Computing program, all the budget will be dedicated to the T&E of the PI and Co-Invs on model development and the experiments during beam development.

Qualifications of PI and Team

The PI, En-Chuan Huang, has been at LANL for five years. As an operation physicist for the LANSCE accelerator, he has brought a preliminary RF signature matching code to full production. The new procedure is exclusively used for the tune-up of the Side-Coupled-Cavity Linac (CCL) this year. The new procedure enables a more robust tune-up with a multifold increase of data for diagnostics at a fraction of the allocated time. Before joining AOT-AE, he spent three years as a postdoc in P-25 on sterile neutrino researches. For the MiniBooNE experiment, he has used the discrepancy between the measured neutrino events and the well-constrained Monte-Carlo model to show an excess at 4.7σ confidence level, which could be potentially explained by the existence of sterile neutrino. He has participated in designing, constructing, and commissioning the first version of the Coherent Captain Mills (CCM) experiment at the Lujan center to search for sterile neutrino via coherent elastic neutrino-nucleus scatterings. He has led the development and testing of the circuit board and readout system for the CCM photo-multiplier tubes (PMTs). Those PMTs are later shipped to Fermilab for the Short-Baseline Near Detector. For his Ph.D., he has worked on the Daya Bay experiment for the precision measurement of θ_{13}. He has also used the data and model differences of Daya Bay to limit allowed parameter space for sterile neutrino.

The Co-Investigator, Charles Taylor, is currently the machine manager for CCL and an operation physicist for LANSCE. He has extensive experience in running the CCL in different conditions, including beam delivery at various energies. He has extensive experience in high energy beam transport and the downstream Proton Storage Ring (PSR) He also led several PSR development, including the delivery of a short pulse to the Lujan Center to increase the instantaneous intensity and an MFR project to solve longitudinal beam instability for high-intensity beams.

The Co-Investigator, Petr Anisimov, is currently the code manager for HPSim in AOT-AE. He has extensive experience in the accelerator simulation, especially in x-ray free electron lasers, and the simulation development of MaRIE.

List of Acryonyms

BPPM	Beam Position & Phase Monitor
CCL	Side-Coupled-Cavity Linac
DAQ	Data Acquisition
HPSim	High-Performance Simulator
LANSCE	Los Alamos Neutron Science Center
PSR	Proton Storage Ring
RF	Radio Frequency
RFSM	RF Signature Matching

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Investigator CVs